A. Standard Membrane Bioreactor Computations

1.0. INTRODUCTION

The following section presents standard computations for membrane bioreactor (MBR) systems. The section outlines important MBR-specific design considerations and calculations, although it is not a complete step-by-step guide to MBR design. Therefore, the design example presented does not address all possible analyses, evaluations, safety factors, or design considerations. Furthermore, the design example assumes the reader has a prior understanding of the design of biological wastewater treatment systems and, therefore, does not address this aspect of MBR design. More information on the general design of activated sludge systems can be found in *Design of Municipal Wastewater Treatment Plants* (WEF et al., 2009). These standard computations focus on understanding key parameters for MBR system design. Depending on the specific parameter and the decision of the engineer and/or owner of the MBR system, these parameters may be specified by the engineer in procurement documents or provided by membrane vendors.

2.0. DESIGN EXAMPLE OVERVIEW

2.1. Design Flowrates and Maximum Monthly Loading Rates

A new MBR facility is being designed to treat influent flows and maximum monthly loading rates, as summarized in Table A.1.

Table A.1 Influent design flowrates and maximum monthly loading rates.

Influent flowrates		
Average annual	8 000	m^3/d
Maximum month	11 500	m^3/d
Peak day	18 000	m^3/d
Peak hour	21 000	m^3/d
Maximum month loading rates		
Biological oxygen demand (BOD)	2 500	kg/d
Total suspended solids	2 400	kg/d
Total Kjeldahl nitrogen	320	kg/d
Ammonia nitrogen	220	kg/d
Total phosphorus	45	kg/d

2.2. Design Temperature

Historical data indicate that the minimum weekly influent temperature is 10 °C; therefore, 10 °C will become the minimum design temperature for the membrane system.

2.3. Treatment Objectives

The MBR treatment system must meet effluent characteristics summarized in Table A.2 on an average monthly basis.

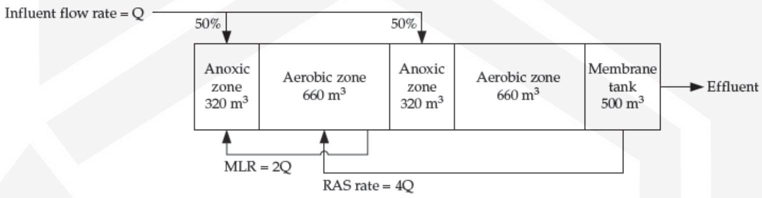
Table A.2 Treatment objectives.

* NTU = nephelometric turbidity units.	
Turbidity	≤ 0.5 NTU *
Total suspended solids	≤ 5 mg/L
Biochemical oxygen demand	≤ 5 mg/L
Total nitrogen	≤ 5 mg/L

2.4. Overview of the Biological Reactor

The biological reactor for this application has been designed to achieve nitrification and denitrification. Because the plant must meet a total nitrogen limit of 5 mg/L, the system has been designed with two sets of anoxic and aerobic zones. The influent flow is split between the anoxic zones to supply organic carbon for denitrification. The treatment plant does not include a primary clarifier, but does include a 2-mm fine screen. The influent fats, oils, and grease (FOG) concentration is expected to be low enough to meet the vendor-specified requirement that the mixed liquor FOG concentration is less than 100 mg/L. The required reactor volume was determined to be 1960 m^3, with 25% anoxic volume. The required membrane tank volume was determined to be 500 m^3 based on the required membrane surface area and the packing density of the selected membrane product. The return activated sludge return pumping system is designed for a flowrate of 4 times the maximum monthly influent flowrate and the mixed liquor return flow returning nitrate to the first anoxic zone is designed for a flowrate of 2 times the maximum monthly influent flowrate. Figure A.1 summarizes relevant flowrates and reactor volumes. The mixed liquor concentration in the biological reactor will range from 6000 to 8000 mg/L total suspended solids (TSS). The design solids retention time (SRT) is 14 days; however, the possible SRT range is from 10 to 20 days. Wastewater flows beyond the peak-day condition will be equalized in a tank upstream of the aeration basin.

Figure A.1 F. A.1 Biological process design overview.



2.5. Membrane Design and Redundancy Requirements

The membrane system will be designed with enough membrane area to accommodate the peak-day flow condition with one membrane train out of service; the MBR will have five membrane trains. The membrane system will also be provided with 10% spare space per membrane train to allow for the installation of additional membrane area if needed. This spare membrane area will not be installed immediately, rather, it will provide contingency for unexpected membrane fouling conditions.

3.0. STANDARD COMPUTATIONS

3.1. Membrane System Design Information

For the purpose of this design example, Table A.3 summarizes relevant membrane system assumptions. These parameters may be specified by the design engineer or provided by the membrane vendor to meet performance criteria specified by the design engineer. No attempt has been made to differentiate these items here.

Table A.3 Assumed membrane design factors.

Membrane area per small subunit	32 m^2
Number of small membrane subunits per large membrane subunit	48
Design flux for peak-day flow based on influent flowrate	30.5 LMH*
Air scour rate for flows up to maximum monthly flowrate	10 seconds on/30 seconds off
Air scour rate for peak-day flowrate	10 seconds on/10 seconds off
Total relaxation interval	12 minutes
Relaxation time	30 seconds
Maintenance clean interval	4 days
Maintenance clean duration	60 minutes
Recovery clean interval	180 days
Recovery clean duration	8 hours
Maximum allowable solids flux to the membrane surface at the net flux of the system	325 $g/m^2 \cdot h$

* LMH = liters per meter squared per hour (standard).

3.2. Parameter Definitions

Table A.4 summarizes the parameter definitions used herein.

Table A.4 Parameter definitions, abbreviations, and units.

Parameter Description	Abbreviation	Unit
Influent flowrate	Q	m^3/d
Design net flux	J	LMH
Instantaneous flux	$J_{instantaneous}$	LMH
Membrane area	A	m^2
Membrane area per small subunit	A_{SSU}	m^2
Time between relaxation	$t_{relaxation}$	minutes
Duration of relaxation	$\tau_{relaxation}$	minutes
Time between maintenance cleans	$t_{maintenance}$	minutes
Duration of maintenance clean	$\tau_{maintenance}$	minutes
Number of relaxations between maintenance cleans	N	
Online factor of the membrane system	η	

3.3. Required Membrane Area

$$J = \frac{Q}{A} \rightarrow A = \frac{Q}{J} = \frac{18\ 000 \,{}^{m^3}\!/\!_{day} \cdot \frac{1000\ \text{L}}{1\ \text{m}^3}}{30.5 \,{}^{\text{L}}\!/\!_{\text{m}^2\text{hr}} \cdot \frac{24\ \text{hr}}{1\ \text{day}}} = 24\ 590\ \text{m}^2$$

(A.1)

In practice, the membrane surface area requirements for all flow conditions and operating scenarios would be assessed against the net flux at those conditions to determine the scenario that drives design of the membrane system. For the current example, the peak-flow condition drives the membrane system surface area requirements.

3.4. Required Number of Small Membrane Subunits with Ten Percent Spare

$$\text{Number of Small Subunits} = \frac{A}{A_{\text{SSU}}} = \frac{24\ 590\ m^2 \cdot 1.10}{32\ m^2} = 840\ \text{Small Subunits}$$

(A.2)

3.5. Required Number of Large Membrane Subunits

$$\text{Number of Large Subunits} = \frac{840}{48} = 18\ \text{Large Subunits}$$

(A.3)

This number of large units requires 4.5 large membrane subunits per membrane tank. The membrane basin is sized to allow installation of five large membrane subunits as a provision for further expansion. Thus, the actual spare membrane area available is 22%.

3.6. Required Membrane Tank Volume

The chosen membrane product requires 20 m^3 per large subunit at the chosen packing density. With five large subunits per membrane train and five total membrane trains, the required membrane tank volume is 500 m^3.

3.7. Instantaneous, Temperature-Corrected Flux

The design flux value of an MBR system is not a measure of the actual flux of the system. Because the membrane system spends time in nonproductive modes of operation (such as relaxation), the actual instantaneous flux during membrane operation must be greater than the design value to treat the full influent flow. Table A.5 illustrates the determination of the instantaneous, temperature-corrected flux values for the peak-day flowrate. It is important to note that the pumping and piping systems for an MBR would be sized to carry the maximum expected instantaneous flowrate. It is also important to note the higher flux value for temperature correction to 20 °C. The designer should always verify the temperature that corresponds to a flux value provided by the vendor or assumed in a design calculation.

Table A.5 Determining instantaneous, temperature-corrected flux.

Number of relaxation cycles per maintenance clean cycle	$n = t_{\text{maintenance}} / t_{\text{relaxation}} = 5760\,\text{min} / 12\,\text{min} = 480$	(A.4)
Time spent in nonproductive relaxation mode	$= n \cdot \tau_{\text{relaxation}} = 480 \cdot 0.5\,\text{min}/cycle = 240\,\text{min}$	(A.5)
Time spent in nonproductive maintenance clean mode	$\tau_{\text{maintenance}} = 60\,\text{min}$	
Online factor	$\eta = 5460\,\text{min} / 5760\,\text{min} = 0.95$	(A.6)
Flux at 10 °C	$J = 30.5\ LMH$	
Instantaneous flux at 10 °C	$J_{\text{instantaneous},10^\circ C} = J / \eta = 32.1\ LMH$	(A.7)
Instantaneous flux at 20 °C	$J_{\text{instantaneous},20^\circ C} = J_{\text{instantaneous},10^\circ C} \cdot 1.025^{20-10} = 41.1\ LMH$	(A.8)

3.8. Peak-Day Solids Loading Rate

The solids loading rate at peak day must be checked to ensure that the design requirement is met. The design net flux is 30.5 LMH at peak-flow conditions. Assuming the membrane tank has a solids concentration of 10 000 mg/L TSS, the solids flux during peak flow is 305 g/m^2·h, which is less than the 325 g/m^2·h maximum provided in Table A.3. However, it is important to note that the maximum allowable solids loading rate to the membrane would be exceeded during peak-day flows if the membrane tank solids concentration is larger than 10 600 mg/L when the peak-day influent flow arrives.

3.9. Air Scour Air Demands

The membrane supplier recommends an air scour rate of 10 Nm^3/h (i.e., normal cubic meters per hour) per small subunit under average conditions and an air scour rate of 20 Nm^3/h per small subunit under peak-flow conditions. The designer has chosen to install enough air scour for the 840 small subunits; therefore, the air scour blowers must be able to provide 8400 Nm^3/h on average and provide 16 800 Nm^3/h under peak-flow conditions. Two alternative approaches available are (1) to provide blower capacity for only the membrane area installed, not including the 22% spare, or (2) to provide blower capacity for the full five large subunits per membrane trains as a provision for future expansion, and throttle the blower, as appropriate, to deliver the required air for the installed membranes.

3.10. Membrane Permeability

Permeability is used as a measurement for determining when a cleaning cycle is needed. Permeability is measured as the temperature-corrected flux divided by the transmembrane pressure (TMP) and, therefore, simultaneously provides information about both membrane flux and TMP, which are critical operating parameters. The membrane manufacturer recommends a maximum typical operating TMP of 0.4 bar. At a temperature-corrected instantaneous flux value of 41.1 LMH at peak-day flow, the minimum allowable membrane permeability is 102.8 LMH/bar.

4.0. RECOVERY CLEANING CALCULATIONS

Performing a recovery cleaning cycle involves emptying the mixed liquor from the membrane tank and then filling it with a chemical solution for cleaning and soaking the membranes. Sizing of the various pumps used for the clean-in-place cycle is a function of the size of the membrane tank, the amount of time allocated to draining and filling the tanks, the chemical used, and the desired chemical solution strength. This section describes typical calculations used for sizing the pumping and chemical systems.

4.1. Membrane Tank Drain Pump

The membrane tank drain pumps are typically used to pump mixed liquor and spent chemical cleaning waste from the membrane tanks. For this example, the drain pumps are sized to empty the membrane tank in 30 minutes. The membrane system has five large subunits that are independently chemically cleaned. Each large subunit is housed in a tank with a volume of 100 m^3. Therefore, the drain pump has a design capacity of 3 m^3/min.

4.2. Recovery Cleaning Chemical Volume

The amount or volume of chemical needed for each recovery cleaning cycle is a function of the size of the membrane tank, the desired solution strength for the chemical cleaning cycle, and the strength of the chemical solution actually delivered or stored at the facility. The membrane manufacturer recommends twice-yearly recovery cleaning cycles, each one lasting 8 hours. The recommended chemical cleaning regime includes 1000 mg/L sodium hypochlorite and 2000 mg/L citric acid. For the purposes of this design example, the volume of sodium hypochlorite required is illustrated in Table A.6. Sodium hypochlorite is delivered to the treatment plant with a concentration 12.5%, by weight, and has a specific gravity of 1.175.

Table A.6 Determination of chemical usage for recovery cleaning.

Mass of sodium hypochlorite required per recovery clean	$= \frac{1\ \text{g NaOCl}}{\text{L}} \cdot 100\ \text{m}^3 \cdot \frac{1000\ \text{L}}{\text{m}^3} = 100000\ \text{g NaOCl}$	(A.9)
Mass of bulk chemical required per recovery clean	$= 100000\ \text{g NaOCl} \cdot \frac{100\ \text{g bulk chemical}}{12.5\ \text{g NaOCl}} = 800000\ \text{g bulk chemical}$	(A.10)
Volume of bulk chemical required per recovery clean	$= 800000\ \text{g} \cdot \frac{1\ \text{mL}}{1.175\ \text{g}} \cdot \frac{1\ \text{L}}{1000\ \text{mL}} = 680\ \text{L bulk chemical}$	(A.11)

5.0. REFERENCE

Water Environment Federation; American Society of Civil Engineers; Environmental and Water Resources Institute (2009) *Design of Municipal Wastewater Treatment Plants,* 5th ed.; WEF Manual of Practice No. 8; ASCE Manual of Practice and Report on Engineering No. 76; McGraw-Hill: New York.